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Energy efficiency analysis and impact evaluation of the application of thermoelectric power cycle to today's CHP systems

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ABSTRACT

High efficiency thermoelectric generators (TEG) can recover waste heat from both industrial and private sectors. Thus, the development and deployment of TEG may represent one of the main drives for technological change and fuel substitution. This paper will present an analysis of system efficiency related to the integration of TEG into thermal energy systems, especially Combined Heat and Power production (CHP). Representative implementations of installing TEG in CHP plants to utilize waste heat, wherein electricity can be generated in situ as a by-product, will be described to show advantageous configurations for combustion systems. The feasible deployment of TEG in various CHP plants will be examined in terms of heat source temperature range, influences on CHP power specification and thermal environment, as well as potential benefits. The overall conversion efficiency improvements and economic benefits, together with the environmental impact of this deployment, will then be estimated. By using the Danish thermal energy system as a paradigm, this paper will consider the TEG application to district heating systems and power plants through the EnergyPLAN model, which has been created to design suitable energy strategies for the integration of electricity production into the overall energy system.

1. Introduction

Thermoelectric technology, which converts heat energy to electric power by means of semiconductor charge carriers, is expected to contribute to meeting today's needs for increased fuel efficiency and reduced harmful emissions. Worldwide, a race has started with the aim of commercializing TEG-based energy saving systems for real life applications. The Japanese national project "The Development for Advanced Thermoelectric Conversion Systems", supported by the New Energy and Industrial Technology Development Organization (NEDO), was initiated in 2002 to create mass production lines and commercial production of TEG systems. A reduction in carbon dioxide emissions of 73,000 tons is prospected and 213 GWh of electric power is generated in 2010 with thermoelectric power generation systems developed in this project [1]. The US Department of Energy recently also initiated a programme on TEG waste heat recovery in relation to automotive and diesel engines, which is one of the sub programmes of the "Advanced Combustion Engines" research plan [2]. The waste heat recovery research focuses on technologies that can recover and convert engine waste heat to electrical energy to improve the overall thermal efficiency of diesel engines to a level higher than 55% towards 60% while reducing emissions to near-zero levels. Fairbanks and Yang spoke about the ambitious plans for practical, industrial-scale thermoelectric waste heat recovery systems [3–5].

In the application of TEG, a frequently asked question is that "how can TEG with a lower conversion efficiency compete with various generators with higher conversion efficiencies?", where Vining shows his insightful but pessimistic concern [6,7]. In our opinion, in the scope of energy harvesting, this is actually not a real barrier, as the TEG will utilize what would otherwise be waste heat, and will not consume fresh fuel for electricity production. Rather than competing with conventional generators, the purpose of most TEG applications is to exploit the low grade heat, cheap or free, and to obtain additional benefits in terms of an improved overall efficiency. Consequently, even for currently used TEG devices with a low conversion efficiency of around 5–10%, they are still strongly advantageous as compared to conventional energy technologies, not only for their well-known merits such as high reliability, silence, low environmental impact, and purely DC electrical power sources, but also because of their capability of utilizing huge amounts of industrial and private waste heat as an energy source in a simple and easy manner. More applications can thus be envisaged, and the development of TEG is expected to become more explosive in the future.

The performance of TEG systems is improved not only due to the elevation of Z-values of the materials but also the progress of the application technique. Excellent review articles have been published on thermoelectric material and technology [6–15], but the

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application of up-to-date TEG power generation to CHP energy systems has attracted much less attention so far. Matsuura analysed a heat pump/TEG system to identify the best use of the cogeneration rather than only to produce electricity, and proposed to apply TEG to the steam turbine of the power station for superconducting synchronous power source, in which part of the steam heat from the turbine is transformed into power by TEG for field excitation [16]. Yodovard et al. assessed the potential of waste heat recovery from the stack exhaust of around 200 °C for diesel engine and gas turbine cogeneration in the manufacturing industrial sector in Thailand [17]. Kyono et al. considered the feasibility of recovering the energy loss at the vapor condensers in the steam-based power plants, utilizing the small temperature difference between the vapor and the coolant, corresponding to around 40 °C and 15–19 °C, respectively [18]. Kametani et al. assumed that TEG modules were mounted between the high temperature exhaust gas heat exchanger (around 600 °C) and cooling water (around 90 °C) of gas engines and gas turbines, respectively, and then examined the effects [19]. However, a systematic analysis of technical pros and cons of these ideas, i.e., the incorporation of TEG into existing CHP energy systems, and especially a comprehensive description on the overall impact of this incorporation, are still absent.

The simple operation of TEG technology as well as its other features make it a feasible supplement to CHP performance improvement. This paper will focus on the technical and economic aspects of the state of the art of large scale TEG applications, using CHP systems in Denmark as a special energy niche. The objective is to describe the technological change represented by the integration of TEG into CHP energy systems and its role as a special kind of fuel substitution. Furthermore, the paper describes how the technological change affects energy consumption by promoting efficiency improvements. The descriptions will begin with an analysis of feasible solutions as well as the technical barriers and challenges for the integration of TEG into thermal energy systems. The representative TEG applications to generic CHP technology are presented sequentially. Following the analysis, the economic and environmental impacts of TEG application are evaluated by use of the EnergyPLAN model [20–25].

2. Applications of TEG to CHP systems

The structure scheme of a typical CHP system is shown in Fig. 1. In general, TEG can be integrated into a CHP in three modes. The first is to place the TEG between the generator and the waste heat boiler, using the temperature difference between the high temperature exhaust gas from the generator and the coolant to produce electricity [19]. The second is to place the TEG at the outlet of the waste heat boiler, using the temperature difference between the final exhaust gas from the boiler and the ambient to produce electricity [17]. The third is to place the TEG at the condenser [18], between the inlet fluid to be warmed and the outlet fluid to be used for heating demand, or in any other place to substitute the traditional heat exchangers, using small temperature differences to produce electricity. The three modes are highlighted in Fig. 1.

2.1. Modelling

In modelling TEG energy systems, an important factor is the dependency of the TEG efficiency on the temperature range. The objective of the aforementioned Japanese national project is to develop high efficiency thermoelectric modules and power generation systems to convert thermal energy of wide and various temperature ranges into electricity. The final goal is to establish a 15% energy conversion efficiency with a temperature difference of 550 K [1]. The interim goal of 12.1% efficiency has already been cleared by Komatsu's bulk material module with a hot side of 580 °C and a cold side of 30 °C [26]. Within the same project framework, another Japanese company YAMAHA proffered Bi–Te based modules for lower temperature applications with a conversion efficiency of 5.6% with around 200 °C as for high temperature side and around 50 °C at low temperature electrode [27]. Other commercially available power modules also display a similar maximum efficiency of about 5% when the operation is in the temperature range of about 200 °C [28]. In [28], it is also shown that the conversion efficiency of the TEG modules can only reach around 1% when the temperature difference is below 50 °C.

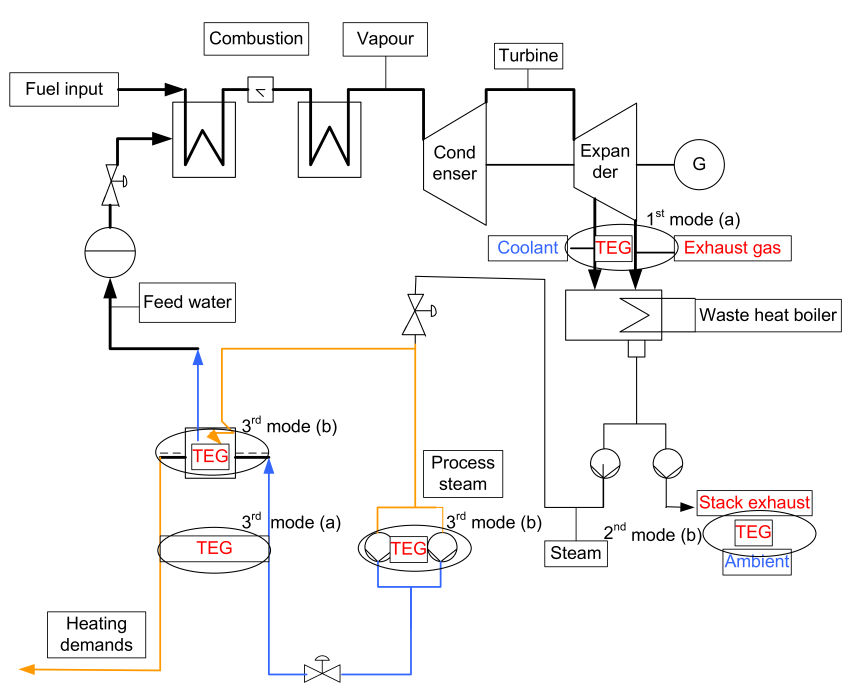

Fig. 1. Schematic representation of a typical CHP system and locations of TEG.

As a basic consensus for modelling, the achievable TEG conversion efficiency has thus emerged that more than 10% for high temperature applications, 5% for middle temperature applications, and 1% for low temperature applications, according to the state of the art of the TEG technology. With the knowledge on the possibilities of utilizing waste heat by installing the TEG near the boiler section and heat production system of CHP plants, we can evaluate the efficiency of TEG in terms of the temperature ranges of the specific location. The basic calculation that will be used for the amount of input energy Q_h to TEG is as follows:

$$Q_h = \text{The amount of released heat} \cdot \text{conversion factor} \tag{1}$$

where the conversion factor is the percentage of the total released heat loss that could be utilized by TEG and is variable in different situations [1].

The change of electricity production of CHP might be found by using the assumption for TEG efficiencies, and thus the potential of incorporating TEG into CHP energy systems can be analyzed after defining the additional electricity output from TEG. Practically, the temperatures of heat sources across the thermoelectric heat exchanger in a large system are however not constant, especially in the case of TEG application shown in Fig. 2a. Therefore, the capacity of TEG used in the efficiency definition is modeled on the basis of the temperature range and the thermal scenario in question.

Let us take the first application mode of TEG in gas and diesel engines as the modelling paradigm. It is advantageous to the others in the sense that a higher conversion efficiency can be obtained due to a higher temperature range, but it is also noteworthy that the first and second modes are different in terms of heat energy flow direction. The difference is illustrated in Fig. 2, in which (a) corresponds to the first TEG application mode whilst (b) corresponds to the second. In Fig. 2a, when the energy flow is in two directions, only part of the utilizable thermal flux contained in the heat source media can be brought into the TEG converter (Q_h). After the electrical power has been extracted, the remaining thermal energy in the coolant will be of lower quality. In Fig. 2b, in which the energy flow is in one direction, all utilizable thermal flux of the heat source will flow into the TEG. Except the proportion of the electric power extracted, most thermal energy will arrive at the coolant which has a lower temperature. For the third application mode, either of the two cases might be applicable depending on the concrete placement of the TEG.

For gas and diesel engines, the waste heat from the generator takes two forms: approximately one third is in the exhaust gas of about 500 °C whilst the other two thirds are in the cylinder water of about 100 °C. If the heat is transferred from the exhaust gas to the cylinder water through TEG, the temperature profile of the exhaust gas will gradually fall along the path from the generator to the waste heat boiler. The temperature profile of the coolant will increase gradually along the same path. Referring to Fig. 2a, if the tubes of heat sources are assumed adiabatic except the heat exchange with TEG, the governing equations of the temperature distribution of the hot and cold fluids, $T_h(x)$ and $T_c(x)$, are

$$m_h c_h dT_h = -n\left[\alpha I T_h(x) + K(T_h(x) - T_c(x)) - \frac{I^2 R}{2}\right]\frac{dx}{w}, \tag{2a}$$

$$m_c c_c dT_c = n\left[\alpha I T_c(x) + K(T_h(x) - T_c(x)) + \frac{I^2 R}{2}\right]\frac{dx}{w}, \tag{2b}$$

where α is the Seebeck coefficient, w the width, K the total thermal conductance and R the internal electrical resistance of a thermocouple; m_h and c_h are constant mass flow rate and specific heat capacity of the hot fluid, and m_c and c_c that of the cold fluid; n is the number of thermocouples mechanically installed in parallel at the same tube position. $\alpha I T_h + K(T_h - T_c) - \frac{I^2R}{2}$ is the well known simplification of Q_h, the rate of heat transfer from the hot fluid to the thermocouple, and $\alpha I T_c + K(T_h - T_c) + \frac{I^2R}{2}$ represents Q_c, the rate of heat transfer from the thermocouple to the cold fluid. Neglecting the temperature drop between thermoelectric device junctions and the attached fluids, the temperature distribution $T_h(x)$ and $T_c(x)$ will determine the efficiency after the TEG is incorporated into CHP systems.

In treating the differential equation system (2) $T_{h,c}(0)$ must be assumed known as the initial conditions of the inlet position. The analytic solution of $T_h(x) - T_c(x)$ can be obtained by further neglecting the Peltier term $\alpha I T_{h,c}(x)$ and the Joule term $\frac{I^2R}{2}$ in $Q_h(x)$ and $Q_c(x)$, where the exponential $T_h(x) - T_c(x)$ are expressed explicitly [18,29]. More precise solution involves the substitution of the equation of the current I,

$$I = \frac{\sum_{i=1}^{L/w} n\alpha(T_h(i) - T_c(i))}{(L/w)nR + R_l}, \tag{3}$$

into (2), where R_l is the load, and the quotient between the tube length L and w calculates the total number of thermocouples in conjunction with n, presumably connected in series in the TEG. By a simple iteration, $T_h(x), T_c(x)$ and I can be solved easily, thus the additional power output from TEG ($P = I^2 R_l$) and the TEG efficiency when operating with varying temperature heat sources $\left(\frac{P}{\sum_{i=1}^{L/w} Q_h(i)}\right)$ are both obtained [30–32].

The equation system (2) and (3) is numerically solved by the mathematic toolkit MATLAB to estimate the system efficiency change. For typical gas and diesel engines in Denmark's CHP plants, the fuel power scale usually falls within the range between 5 MW and 20 MW. If the fuel power of an engine is assumed 10 MW, and the electrical efficiency η_{el} is assumed 40% in the original CHP, the thermal power contained in the generator exhaust would be one third of 6 MW, i.e.,

$$Q_{exhaust} = m_h c_h (T_h(0) - T_{ambient}) = \frac{1}{3} \cdot 6\ \text{MW} = 2\ \text{MW}, \tag{4}$$

where c_h is close to the specific heat capacity of air, which is about 1 KJ/kg K. Substituting $T_h(0) = 500\,°C$, m_h can be calculated as about 4 Kg/s. Similarly, by

$$Q_{cylinder} = m_c c_c (T_c(0) - T_{ambient}) = \frac{2}{3} \cdot 6\ \text{MW} = 4\ \text{MW} \tag{5}$$

and $T_c(0) = 100\,°C$, m_c can be calculated as about 10 Kg/s. The calculation methodology of these numbers is used in conjunction with constant thermoelectric properties (α = 0.00044 V/K, R = 0.0178 Ω, K = 0.0034 W/K) in the following simulation.

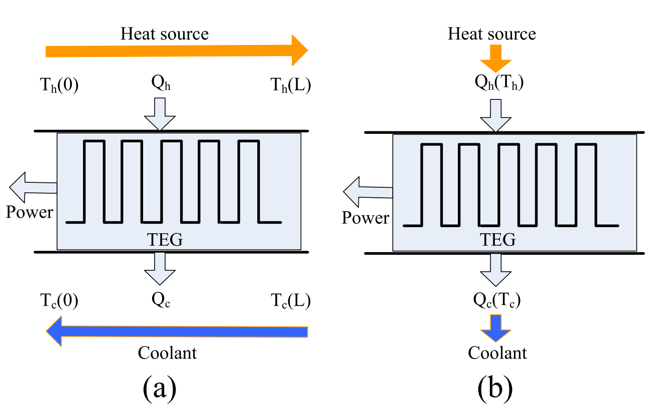

Fig. 2. Heat flow supplying modes to TEG in practical operation. (a) Energy flows two dimensionally and (b) energy flows one dimensionally.

2.2. Evaluation of the system efficiency

Let us now analyze the three integration modes from the technical viewpoint one by one. For gas and diesel engines, when a typical design of 20 m is adopted as the exhaust tube length, i.e., $L = 20$ m, the outlet temperature $T_h(L)$ is found to be 455 °C, and $T_c(L)$ 103.65 °C by the above model. Consequently, the thermal efficiency η_{boiler} of the boiler will be degraded because of the lower exhaust gas temperature, but might be compensated by the higher cylinder water temperature. If an offset of balance is created, i.e., η_{boiler} is not changed, the performance improvement can be shown by a simple calculation. In the original CHP, we assume that η_{el} is 40% and the thermal efficiency η_{th} is $(1-\eta_{\text{el}})\eta_{\text{boiler}}$, respectively, where η_{boiler} is equal to $\frac{5}{6}$. So the total efficiency η is

$$\eta = \eta_{\text{el}} + \eta_{\text{th}} = 40\% + (1-40\%)\frac{5}{6} = 90\%. \tag{6}$$

The heat transferred towarding the cylinder water through TEG (Q_h) is calculated as 187,690 W, which is close to 10% of the total heat contained in the exhaust gas. Then the improved electrical efficiency η_{el} is estimated as

$$\begin{aligned}\eta_{\text{el}} &= 40\% + (1-40\%)\cdot\frac{1}{3}\cdot\frac{187{,}690}{2{,}000{,}000}\cdot\eta_{\text{TEG}}\\ &\approx 40\% + 60\%\cdot\frac{1}{3}\cdot 10\%\cdot 15\% = 40.3\%,\end{aligned} \tag{7}$$

where η_{TEG} is the TEG efficiency calculated to be 15.47% hereby. η_{th} becomes to

$$\begin{aligned}\eta_{\text{th}} &\approx [(1-40\%)\cdot\frac{1}{3}\cdot 90\% + (1-40\%)\cdot\frac{2}{3} + (1-40\%)\cdot\frac{1}{3}\\ &\quad\cdot 10\%\cdot(1-\eta_{\text{TEG}})]\cdot\eta_{\text{boiler}}\\ &\approx 59.7\%\cdot\frac{5}{6} = 49.75\%.\end{aligned} \tag{8}$$

Obviously, after the TEG technology is incorporated the performance of the CHP is preferable to the original production even the total efficiency η is almost the same, since electricity is an energy source of higher quality than heat.

For most other types of CHP, including gas turbines and steam-based turbines fuelled by coal, biomass, or solid waste, the waste heat from the generator is different from that of gas and diesel engines. The gas turbines, for instance, have waste heat of very high quality, mainly contained in the exhaust gas flow of about 500 °C, which can be conveniently recovered in the steam form by the waste heat boiler. In order to create the temperature difference required for the TEG to work, the coolant of lower temperature (<50 °C) must be used as the cold source. If the energy transferred from the exhaust gas to the coolant is not utilized furthermore, then with alike modelling strategies and assumptions the improved electrical efficiency η_{el} is calculated as

$$\eta_{\text{el}} = 40\% + (1-40\%)\cdot\frac{218{,}840}{6{,}000{,}000}\cdot\eta_{\text{TEG}} \approx 40.4\%, \tag{9}$$

where 218,840 W is the heat transferred from the exhaust gas to the TEG (Q_h) by the simulation. η_{th} is calculated as

$$\eta_{\text{th}} = (1-40\%)\cdot\frac{6{,}000{,}000 - 218{,}840}{6{,}000{,}000}\cdot\eta_{\text{boiler}} \approx 48.2\%. \tag{10}$$

If the energy transferred from the exhaust gas to the coolant can also be utilized by the waste heat boiler, or by any other waste heat recovery means, then η_{th} should be

$$\begin{aligned}\eta_{\text{th}} &= [(1-40\%)\cdot\frac{6{,}000{,}000-218{,}840}{6{,}000{,}000} + (1-40\%)\\ &\quad\cdot\frac{218{,}840}{6{,}000{,}000}\cdot(1-\eta_{\text{TEG}})]\cdot\eta_{\text{boiler}}\\ &\approx 59.6\%\cdot\frac{5}{6}\approx 49.7\%.\end{aligned} \tag{11}$$

Thus the total efficiency η is around 90.1%, not far from the original value. But additional benefits of generating extra electricity are obtained after the TEG technology is incorporated into the CHP systems.

The second mode can provide a hot source to TEG only at a temperature of 200 °C by the final exhaust gas. However, all the utilizable heat contained in the exhaust gas is transferred to the surroundings through TEG, as is shown in Fig. 2b. This represents a simpler mode of electricity production. If we again assume that 90% of the total energy is originally utilized in the CHP power plant, then the improved electrical efficiency η_{el} is

$$\eta_{\text{el}} = 40\% + (1-90\%)\cdot\eta_{\text{TEG}} = 40.5\% \tag{12}$$

where η_{TEG} is the TEG efficiency assumed to be 5% hereby because of the lower hot source temperature. $\eta_{\text{th}} = 50\%$ is not changed by the TEG.

The third mode works at the lower temperature range of about 50 °C. The heat, usually carried by steam, is planned to meet the heating demand of hot water, warming, chilling, and process steam, etc. Because η_{TEG} is sharply decreased in this scenario, the effects which the energy transfer mode in Fig. 2a has on the large scale application could be negligible. Here, we only look at the mode in Fig. 2b, i.e., applying TEG to substitute the traditional heat exchangers. Without change of the total efficiency η, extra electricity can be produced as a by-product. η_{el} is

$$\eta_{\text{el}} = 40\% + (1-40\%)\cdot\eta_{\text{boiler}}\cdot\eta_{\text{TEG}} = 40.5\% \tag{13}$$

where η_{TEG} is the TEG efficiency assumed as 1% hereby. η_{th} is subtracted by the power of TEG, equal to 49.5%.

2.3. Technical barrier analysis

We are now able to draw a series of sub-conclusions with regard to technical aspects in the application of TEG to CHP systems:

(i) in the first mode wherein TEG can extract power by the temperature difference between the high temperature exhaust gas from the generator and the coolant, the electrical efficiency η_{el} can be increased to a certain extent. Meanwhile for gas and diesel engines, the thermal efficiency η_{th} and the total efficiency η can be maintained at a similar level. For other types of CHP, η_{th} and η can still be kept, provided that the energy transferred from the exhaust gas to the coolant can be utilized anyhow. Of course, the assumptions that η_{boiler} is not changed when TEG are included, and that the energy transferred from the exhaust gas to the coolant can be effectively utilized with a conversion efficiency as high as η_{boiler}, are both plausible in a strict sense. In the practical operation of any CHP, the design of efficiency specification should be examined case by case more carefully. It is, however, beyond the scope of this article to estimate the general impacts of the TEG on CHP systems.

(ii) in the first mode it is found that the improvement brought by TEG is sensitive to the length of the fluid tubes. The simulation shows that the TEG power will become negligible when compared with the CHP power scale if the tube length is significantly decreased. For instance, if a design of 2 m is adopted instead of 20 m as the exhaust tube length for the aforementioned 10 MW engine example, η_{el} of the CHP can

only be increased to 40.029% since the number of thermoelements is only about 10% of the original design. Of course, longer tubes involves many technical and economic considerations, and these issues also need to be examined carefully in practical applications.

(iii) in the second mode wherein TEG can extract power by the temperature difference between the low temperature exhaust gas from the waste heat boiler and the ambient, the electrical efficiency η_{el} can be increased to a certain extent with a similar thermal efficiency η_{th} and total efficiency η. However, the underlying assumption that no temperature change of the boiler will take place should be examined carefully in any practical design in order to prevent the consequential possibility of corrosion of the boiler chimney.

(iv) in the third mode wherein TEG can extract power by the small temperature difference between the heating fluid from the waste heat boiler and the coolant, the electrical efficiency η_{el} can be increased to a certain extent. Although the decrease of thermal efficiency η_{th} or total efficiency η by the power is tiny, the consequential influences in terms of meeting heating demands should be guaranteed to be at an acceptable level.

(v) From economic viewpoint, the marginal cost for such TEG applications is mainly caused by the thermoelectric materials used. Although a detailed analysis is still beyond the scope of this article, a rough cost estimation can be obtained from the open price of commercial TEG modules [28]. Using the simulation example of the 20 m exhaust tube of the 10 MW engine, the quotient between commercial module price per unit volume [28] and the TEG volume shows the marginal cost in this case is about 3000–4000 US$, which means that the marginal cost is a little more than 0.1 US$ per watt. This value is significantly lower than that in the previous analysis [33,34] due to the significantly higher heat source temperature herein, and for the second and third modes the marginal cost should be changed according to the actual temperature ranges. Certainly, advanced thermoelectric materials with same or better cost-effectiveness, performance, and reliability as or than the commercial TEG in high temperature applications is the main technical barrier in reducing the marginal cost.

3. Danish thermal energy system analysis

3.1. EnergyPLAN model and the analysis methodology

The EnergyPLAN model has been created to analyse and design suitable Danish national strategies for the integration of electricity production from traditional and renewable resources into the overall energy system. The model is divided into two parts. The first part makes a technical analysis based on demands and capacities. The second part makes an economic optimisation of the system behaviour based on further inputs of marginal costs and hour-by-hour international electricity market price assumptions. The inputs of EnergyPLAN include demands (annual district heating and electricity consumption) and capacities (solar thermal, industrial CHP heat production inputs to district heating, capacities and operation efficiencies of CHP units, power stations, boilers and heat pumps). Its outputs include energy balances and resulting annual production, fuel consumption and import/export. One of the analysis paradigms of the model is the large-scale integration of wind power and renewable energy sources. This paradigm has been developed by modelling the western Danish energy system in the year 2020 on the EnergyPLAN computer model [20].

In the application of EnergyPLAN to the scenario called reference2030, the electricity production from CHP is found by applying the assumed efficiencies. In the case of CHP energy systems integrated with TEG, these assumptions must be modified in EnergyPLAN in a way that new outputs of the model can describe the overall system conversion efficiency improvements achieved by TEG together with economic benefits and potential environmental improvements. If other configurations in the model are changed, it is also possible to further examine how the energy system can be designed in terms of various special scenarios in order to benefit from TEG.

Hence, the EnergyPLAN modelling in this article consists of six steps:

1. Load the input data set, a model of a Danish business as usual scenario, from the national energy authority made in 2006.
2. Set the import/export transmission and choose technical regulation strategy.
3. Modify electrical and thermal efficiencies of CHP energy systems in the model in terms of the principle expounded in Section 2.
4. Modify the electricity production from CHP, i.e., capacities of CHP in the model, in terms of the modified efficiency in Step 3.
5. Modify the energy system design configuration in the model (optional).
6. Output the results.

3.2. Danish district heating systems

The main heat releasing sources in Denmark could be classified into two categories, namely the waste heat loss in energy conversion and distribution and the waste heat loss in final energy consumptions [35]. According to this classification, we shall consider the CHP plants in the energy conversion and distribution sector. Specially three kinds of heat and power producing devices are chosen for the analysis (see figure in [35]), i.e., district heating plants, small scale central heating plants and large power stations, in which a technical integration of TEG is most likely.

Denmark is a special country in terms of co-generation and district heating systems. Conventional fuel heating systems and combustion units for heat production and conventional power plants for electricity production make ways for decentralized thermoelectric co-generation mode, i.e., so called district heating systems. Although Danish district heating systems consist mainly of large power stations, yet there are many small scale co-generation central heating plants and district heating plants that only produce heat in Denmark. In the long winter (normally from September to May), the main heat demand of individual communities is met by exhaust gas, steam, and water released from turbines of different electricity generators. In other words, the heating systems of city districts are used as the cooler of power plants.

Small scale central heating plants produce hot water for district heating. But at the same time they also produce electricity for the grid as a byproduct, because their main focus area is the hot water production. The plants are based on different electricity producing devices, for example:

1. Reciprocating engines (mainly gas fired)
2. Gas turbines (mainly gas fired)
3. Gas and steam turbines, combined cycle plants (mainly gas fired)
4. Steam turbines (solid fuel as coal, straw, wood pellet)

The two first mentioned devices are characterized by a high temperature for heat addition and a high temperature for heat

rejection to the district heating. Therefore, there is a large temperature difference between the exhaust gases and the district heating water, and thus a good opportunity for placing TEG devices using the first mode without affecting the existing electricity production/efficiency. Moreover, for all the plants, exhaust gases are cooled down to such a low temperature as can be accepted to prevent corrosion. In this area, it is possible to place TEG and use TEG to cool down exhaust gases, where electricity is produced through the second mode.

On the other hand, in the two last applications the temperature for heat rejection to the district heating water is quite low. Hence, the electricity production and the electricity efficiency of the existing plant will be influenced by the use of TEG. In contrast to plant types described above, the electricity production is the main product of large power stations, though the waste heat is also used for district heating. Since the electrical efficiency of these steam turbine based plants is highly optimized, it is not possible to use TEG through either the first mode or the second mode without affecting the already existing electrical efficiency. Because the temperature difference between the heat rejected and the district heating water is very small, around 10 °C, the third usage is not of interest.

Therefore, the effective use of TEG in steam turbine based CHP in district heating systems in winter is not technically feasible due to the fully optimized overall efficiency (as high as up to 90%). High efficiency simply means that the improvement potential is small, and only a minor amount of thermal energy can be utilized by TEG. In summer (from June to August), however, the main heat demand sharply decreases. The main task of the CHP plants is therefore changed to electricity generation, and their overall efficiency is lowered to around 50%. In this period of time, TEG could be used as a cooler of the plants instead of using district heating systems for this purpose. The cold sea water, which is currently being used in summer, can be employed to cool the TEG.

In addition, district heating plants produce hot water mainly in detached family houses (hot water district heating) in some counties of Denmark, in parallel with those aforementioned centralized heating systems in all towns. These district heating plants are based on fuels like biomass (wood pellet, straw), oil, coal and natural gas. They have no electricity production, which means a great potential in terms of applying TEG due to their high combustion temperatures and the possible coolant by district heating water. In this way, the nature of these district heating plants will be changed from HP to CHP, however small the proportion of the generated electricity is.

3.3. Results of CHP at district heating systems

In applying EnergyPLAN to situations closer the practical one, we assume the same total efficiency at nearly 90% for all the following cases. This means that every time an improved electrical efficiency of one per cent is assumed, we also assume that the thermal efficiency is reduced by one per cent in order to keep the total efficiency at the same level as the original value. The impacts of applying TEG to each CHP system, and the overall impacts when the applications are combined, can therefore be estimated.

Taking both large power stations and small scale central heating plants into account, the annual environmental and economical impacts of introducing TEG are shown in Figs. 3 and 4, respectively. Note that the district heating plants which only produce heat are not considered to include TEG in this work. In all cases the maximum import/export capacity of the Danish energy system is assumed to be 0 MW, i.e., no exchange with the international market is assumed. The open market strategy would involve many complicated factors. In order to evaluate the impacts of introducing TEG in Denmark, various reference energy models are here analysed for a closed Danish energy system.

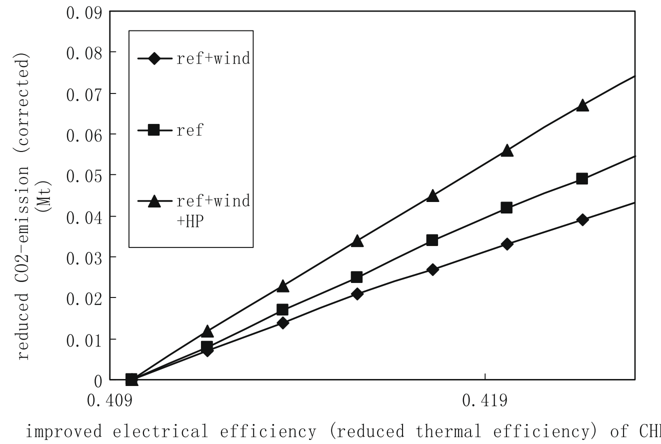

Fig. 3. The environmental effect of TEG in CHP at district heating systems. (ref: reference energy model without heat pump and wind power meeting moderate electricity demand; ref + wind: reference energy model without heat pump and wind power meeting essential electricity demand; ref + wind + HP: reference energy model with heat pump and wind power meeting essential electricity demand).

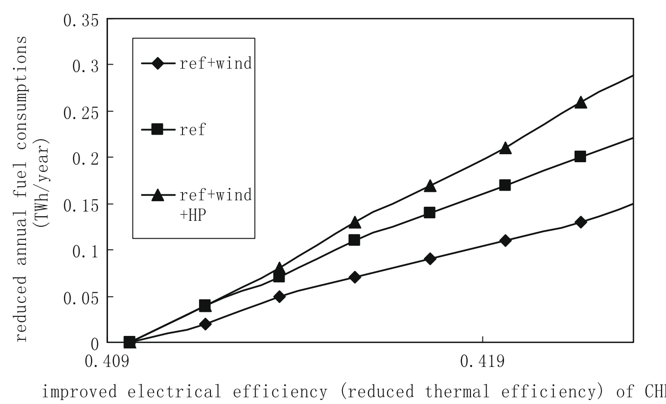

Fig. 4. The economical effect of TEG in CHP at district heating systems. (ref: reference energy model without heat pump and wind power meeting moderate electricity demand; ref + wind: reference energy model without heat pump and wind power meeting essential electricity demand; ref + wind + HP: reference energy model with heat pump and wind power meeting essential electricity demand).

Generally speaking, the reductions in emissions and fuel consumptions achieved by introducing TEG are noticeable seen in relation to their original values. With more efficient TEG, further reductions in emissions and larger fuel savings can be achieved. If the technical regulation strategy meeting only the heat demand is used, it can be seen that the absolute amount of emissions and fuel reductions achieved by applying TEG is decreased when the proportion of renewable energy is increased (ref + wind, where the wind power is increased to meet from about 30% to half of the annual electricity demand). It is also interesting to check the influence brought by TEG for different energy system configurations and technical regulation strategy. The strategy meeting both the heat and electricity demand and the heat pump scenario with more electricity consumption are considered and designed with the objective of utilizing the extra power produced by TEG (ref + wind + HP, where heat pump capacities are assumed to be 100 MW e and 575 MJ/s for small CHP, and 350 MJ/s for large CHP, respectively). It can be seen that, within Denmark, the amount of emissions and fuel consumptions reduced by TEG is

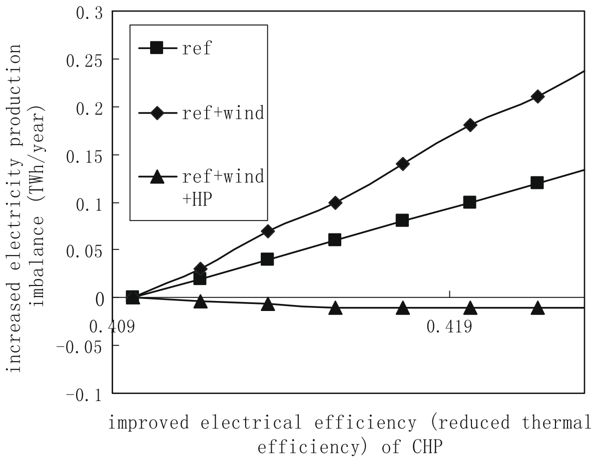

Fig. 5. Annual excess electricity production. (ref: reference energy model without heat pump and wind power meeting moderate electricity demand; ref + wind: reference energy model without heat pump and wind power meeting essential electricity demand; ref + wind + HP: reference energy model with heat pump and wind power meeting essential electricity demand).

much more than in the cases without heat pump, even when the wind power still meets the essential electricity demand.

In order to demonstrate that the energy system can be optimized to further benefit from TEG, the same configurations of the three reference energy models are implemented in EnergyPLAN to analyse the changes of excess electricity production brought by TEG, as shown in Fig. 5. No measure like reducing renewable power production, replacing CHP with boiler, or replacing boiler with electric heating, will be performed on the excess electricity to differentiate this analysis from those others in Figs. 3 and 4. Since the excess electricity in the closed system is not taken away, the potential of TEG for excess electricity becomes fairly obvious for the basic reference energy model (ref), and more excess electricity can be envisaged as the share of wind power production increases (ref + wind). However, it is interesting to find that when CHP heat pump capacities are included (designed to be 100 MW e), the imbalances even decrease in the system and a balanced electricity production has almost been reached (ref + wind + HP). This is due to the fact that the introduction of TEG leads to an increase in the electric output of CHP, but the CHP heat output decreases and leaves more room for the heat pump to produce heat and, consequently, consume electricity. This, again, leads to a slight reduction in the excess electricity production. Based on these examples, it is clear that the co-design of energy system configuration and renewable energy policy will be the key to a successful large-scale TEG application.

4. Concluding remarks

The EU commission has recently agreed on the imperative energy policy to reduce 20% of the greenhouse gas emission and to increase the share of renewable energy in Europe to 20% by 2020. The analyses presented in this paper provide an complementary idea of how to realize this ambition. Compared to the reduction of emissions through other technologies, the simple and reliable waste heat conversion by TEG should be more actively considered for CHP power plants of various sectors. In this regard, the comparatively small niche of Danish energy system provides an appropriate testing place for novel energy technologies such as TEG because explorative experiments can be carried out with less influences. The main results obtained herein can create the basis for the development of the associated energy policy, the planning of future energy requirements, and the estimation/forecasting of environmental impacts such as greenhouse gases emissions. Although the final solution of the cost problem depends on the endeavour of the people in different sectors, the promotion of TEG applications is expected to have a significant impact on Danish and international energy infrastructures.

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